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Constraining R-parity violating couplings using dimuon data at Tevatron Run-II.

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Abstract

The dimuon plus dijet signal is analyzed in the top squark pair production at Tevatron Run-II experiment and the total event rate is compared with the existing dimuon data. This comparison rules out top squark mass upto 188(104) GeV for the branching fraction 100%(50%) of top squark decay into the muon plus quark via lepton number violating coupling. Interpretation of this limit in the framework of R-parity violating(RPV) SUSY model puts limit on relevant RPV coupling for a given top squark mass and other supersymmetric model parameters. If $m_{\tilde{t}_1} \lesssim 180$ GeV we found that the RPV couplings are roughly restricted to be within $\sim 10^{-4}$ which is at the same ballpark value obtained from the neutrino data. The limits are very stringent for a scenario where top squarks appear to be the next lightest supersymmetric particles.

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The Minimal Supersymmetric Standard Model(MSSM) [1] is a theoretically well motivated and also a very strong candidate for beyond standard model(SM) physics. Although,so far, there is no experimental evidence of Supersymmetric(SUSY) theory, nevertheless, in all current and future high energy collider based experiments, looking for SUSY is one of the very high priority programs. The MSSM contains all SM particles in addition to their corresponding SUSY partners and at least two higgs doublets which are the ingredient to switch on the electroweak symmetry breaking mechanism to generate masses of all physical particles. Lack of evidence in degeneracy of masses among particles and corresponding sparticles implies that SUSY is not a exact symmetry, it has to be broken. In MSSM, a mixing occurs among different chiral states of sfermions($\tilde{f}$), superpartners of fermions(f). Since the extent of mixing is proportional to the corresponding fermion mass, m_f, naturally, the mixing between the third generation of left and right handed sfermions, $\tilde{f}_L, \tilde{f}_R$ becomes more stronger than the case of other two generations of sfermions [2]. As a consequence, there is a large splitting between the mass eigen states $\tilde{t}_1$ and $\tilde{t}_2$(assume $m_{\tilde{t}_1} \leq m_{\tilde{t}_2}$) of top squarks(SUSY partners of top quarks). Moreover, because of large Yukawa coupling, the soft SUSY masses $m_{\tilde{t}_L}, m_{\tilde{t}_R}$ receive a significant corrections via the renormalization group equation [3] which results more splitting between the masses of $\tilde{t}_1$ and $\tilde{t}_2$ states. Incidentally, it may happen that for a certain region of SUSY parameter space the lighter state of top squark, $\tilde{t}_1$, turns out to be the next lightest SUSY particle(NLSP), where the lightest neutralino, $\tilde{\chi}_1^0$, is assumed to be the lightest SUSY particles(LSP).

The decay pattern of $\tilde{t}_1$ is phenomenologically very interesting. In the R-parity conserving(RPC) model a scenario where $m_{\tilde{t}_1}$ is heavier than the mass of the lighter chargino $m_{\tilde{\chi}_1^\pm}$, the charged current decay mode of $\tilde{t}_1$ via a b quark and $\tilde{\chi}_1^\pm$

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \tag{1}$$

dominates. Otherwise, $\tilde{t}_1$ mainly decays via the loop induced flavor changing neutral current decay mode [4],

$$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \tag{2}$$

and as well as via the four body decay mode into a b quark, LSP and two massless fermions,

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 f\bar{f}' \tag{3}$$

The competition between these two decay channels in absence of charged current decay mode, Eq. 1 mainly controlled by SUSY parameter space [5]. Along with all these decay channels, in the framework of R-parity violating(RPV) SUSY model, $\tilde{t}_1$ can have also other decay channels via lepton number violating couplings of class λ'_{i3j},

$$\tilde{t}_1 \rightarrow \ell + q \tag{4}$$

assuming baryon number violating interactions are forbidden. Here $i(j)$ stand for the lepton(quark) family index. Of course, the search strategy of top squark in hadron colliders is

decided by the decay pattern of $\tilde{t}_1$. In RPC SUSY model, the detailed study of top squark searches has already been presented in Ref. [6, 7, 8] where as the discovery potential of $\tilde{t}_1$ for RPV SUSY model are discussed in recent studies [9].

In RPV SUSY model, neglecting the masses of leptons and quarks, the decay width of $\tilde{t}_1$ into a lepton and a quark solely depends, for a given RPV λ'_{i3j} coupling, on the mass of $\tilde{t}_1$ state and $\cos\theta_{\tilde{t}}$, where $\theta_{\tilde{t}}$ is the mixing angle between two chiral states $\tilde{t}_L$ and $\tilde{t}_R$. As a consequence of this decay channel, in this model, the pair production of top squark is signaled by di-lepton plus di-jet without missing energy in the final states [1]. For a given luminosity, the total event rate, of course, depends on the branching ratio, ϵ^{ℓ}_{br}=BR($\tilde{t}_1 \to \ell + q$) which is given by,

$$Br(\tilde{t}_1 \to \ell + q) = \frac{\Gamma_{\not{R}}(\tilde{t}_1 \to \ell + q)}{\Gamma_{\not{R}}(\tilde{t}_1 \to \ell + q) + \Gamma_R(\tilde{t}_1 \to all)} \tag{5}$$

Here $\Gamma_{\not{R}}(\tilde{t}_1 \to \ell + q)$ stands for the total decay width of $\tilde{t}_1$ in the RPV channel where as $\Gamma_R(\tilde{t}_1 \to all)$ presents the total decay width of $\tilde{t}_1$ for all possible kinematically allowed channels in RPC model. Needless to say that for a given $m_{\tilde{t}_1}$, ϵ^{ℓ}_{br} is very sensitive to λ'_{i3j} and $\cos\theta_{\tilde{t}}$ and as well as to the total decay width of $\tilde{t}_1$ in all accessible RPC decay channels of $\tilde{t}_1$. However, the total decay width of $\tilde{t}_1$ in all RPC channels depends on SUSY parameters, mainly sensitive to M_2 - the SU(2) gaugino mass[2], μ - the higgsino mass parameter and $\tan\beta$, the ratio of two vacuum expectation values required to generate masses of particles in the model. The pattern of ϵ^{ℓ}_{br} has been investigated in detail for a wide range of SUSY parameter space [9]. It is found that the RPV decay mode, Eq.4, is very competitive and dominates over the other two decay channels, Eq.2 which is loop suppressed and Eq. 3 which is suppressed because of its four body final state. Interestingly, for a substantial region of SUSY parameter space, this RPV decay mode dominates over these two decay modes even for a smaller value of RPV couplings $\lambda'_{i3j}(\sim 10^{-4})$ [9]. However, this is not the case when $\tilde{t}_1$ is allowed to decay via charged current decay mode, Eq.1, in the scenario $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^{\pm}}$ i.e when $\tilde{t}_1$ is not the NLSP. In this scenario, the RPV decay channel requires large value of λ'_{i3j} to make it competitive with the charged current decay mode [9].

We can argue that, if the RPV SUSY model be a viable model, then the signature of this model may be found through the top squark pair production which has comparatively larger cross section as $\tilde{t}_1$ is likely to be the lightest colored sparticle via its decay channel Eq.4. The search prospect of $\tilde{t}_1$ at Run-II in Tevatron experiment in the framework of RPV model has been discussed in detail in Ref. [9] for the class of λ'_{i3j} RPV coupling. The discovery potential of $\tilde{t}_1$ are thoroughly discussed in the dilepton plus dijet channel in a model independent way. The range of λ'_{i3j} which can be probed for a given luminosity is also presented [9]. The present study is devoted to investigate the signal of $\tilde{t}_1$ state in the di-muon plus dijet ($\mu\mu +$

[1] In case of τ lepton some amount of missing energy will appear because of the presence of ν_τ from τ decay.

[2] Assuming the gaugino mass relation $M_1 \simeq M_2/2$

jj) channel because of the decay $\tilde{t}_1 \to \mu + q$ via the lepton number violating RPV coupling λ'_{23j}. Eventually, a comparison is made between our predicted event rates with the existing preliminary data which was analyzed to study the signal of second generation of Leptoquark searches in D0 detector at Tevatron Run-II experiment [10] with $\sqrt{s}$ =1.96 TeV. It is worth to mention here that in our earlier study, we analyzed the di-electron plus dijet final state from top squark pair production and its subsequent decay, $\tilde{t}_1 \to e + q$, via RPV coupling λ'_{13j} [11] and compared the predicted event rates with the existing dielectron data in D0 detector at Run-I. The di-electron plus di-jet data was reported in the context of first generation of Leptoquark searches of which final state event topology is same as the final state containing di-electrons plus di-jets. We concluded from that study that $m_{\tilde{t}_1} \gtrsim$220 GeV can be ruled out for 100% decay of $\tilde{t}_1$ in the channel,Eq. 4. Moreover, in the framework of RPV SUSY model we excluded certain region in the $m_{\tilde{t}_1} - \lambda'_{13j}$ plane for a given SUSY parameter space [11].

It is interesting to note that for a long time RPV SUSY models has been known as a viable option which can provide models of neutrino mass [12]. These models have attracted special attention after the neutrino data confirms that the neutrinos are not massless [13]. Clearly, the parameters which participate in the process of neutrino mass generation in a given model can be constrained using neutrino data and obviously it will be model dependent prediction [14, 15]. For example, for a certain class of models where λ'_{i33} lepton number violating couplings are required to generate neutrino masses are restricted to be within the range of $\sim 10^{-3} - 10^{-4}$ depending on the magnitude of soft breaking masses in RPC SUSY theory [15]. Certainly, these bounds are more stronger than the previous bounds prior to neutrino data [16]. Notably, our previous analysis in the $ee + jj$ channel predicts upper bounds on the same set of RPV couplings which are at the same ballpark [11]. At Tevatron Run-II, the implications of these relevant RPV couplings has been studied in detail very systematically [9]. We notice that it is quite possible to find the signal of RPV SUSY if the RPV couplings are in the vicinity of these predicted bounds. This interesting observation motivates us to further extend our study in the $\mu\mu + jj$ channel in RPV SUSY model and similarly as before [11], examine the value of RPV coupling λ'_{23j} allowed by the existing dimuon data [10]. In the past, using Tevatron data there was a attempt to constrain squark and gluino masses [17] and RPV couplings [18] in the framework of RPV SUSY model. In the next section we describe our analysis and discuss our results with a summary at the end.

At Tevatron top squark pair production takes place via $q\bar{q}, gg \to \tilde{t}_1\tilde{t}_1^*$ and the magnitude of cross section depends mainly on $m_{\tilde{t}_1}$ [19]. The QCD correction enhances the cross section by ∼30% roughly, although this correction depends on the choice of QCD scales Q^2 [20] which we set to $Q^2 = \hat{s}$. In our calculation we used CTEQ5L parametrization for incoming parton flux. As explained earlier, focusing our signal to $\mu\mu$+jj final state which arises due to $\tilde{t}_1$ decay, $\tilde{t}_1 \to \mu + q$ via λ'_{23j} RPV coupling we intend to compare total event rates of this final state with the existing Run II di-muon result [10]. The event generator `PYTHIA` [21] has been used to generate events from $\tilde{t}_1$ pair production and then forcing $\tilde{t}_1$ to decay in the $\tilde{t}_1 \to \mu + q$ channel. The hadronisation effects with the initial and final state radiation has been considered during event generation. We have used `PYCELL` [21] for jet formation. Note that we have not performed any detector simulation in our analysis. We have used `PYTHIA`

mainly to find the geometrical and kinematic selection efficiencies for the set of cuts defined in [10]. Eventually, we obtain the signal cross section by multiplying selection efficiency along with all other detection efficiencies due to triggering, muon isolation and identification, jet reconstruction and tracking efficiencies as quoted in Ref. [10].

In our analysis we have applied the same set of kinematic cuts [10] on final state particles which are optimized mainly to suppress the SM backgrounds, particularly from $t\bar{t}$, WW pair production and Drell-Yan process. The selection cuts are as following: (i) muons are selected if, $p_T^{\mu} > 15$ GeV,$|\eta| <1.9$ and dimuon invariant mass $M_{\mu\mu} > 60$ GeV, muon isolation is confirmed by demanding $E_{0.4} - E_{0.1} < 2.5$ GeV where $E_{0.4(0.1)}$ is sum of the energy of the particles contained in a cone of size 0.4(0.1) in η-ϕ space around muons. Note that we smear the muon momenta as done in Ref. [10]. (ii) jets are required to have $E_T^j > 25$ GeV, $|\eta_j| <2.4$ and two or more jets are accepted with $\Delta R =0.4$, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The efficiency for jet reconstruction with $E_T^j > 30$ GeV is given to be greater than $96 \pm 3\%$ [10]; (iii) Dimuon invariant mass is demanded to be $M_{\mu\mu} >110$ GeV; and (iv) $S_T > 280$ GeV where $S_T = \sum_{i=\mu\mu jj} E_T^i$.

Cuts (i) and (ii) are basically the preselection requirements to select events. Selection cut (iii) is mostly to eliminate the background, mainly, from $Z \to \mu\mu$ where the events are distributed around the Z-peak, and finally, selection criteria (iv) on scalar sum of visible transverse energy takes care of rest of the background cross sections. The number of signal events are:

$$n_{sig} = \sigma_{\tilde{t}_1\tilde{t}_1}.\epsilon_{br}^{\mu}.\epsilon_{ac}.\tilde{L} \tag{6}$$

$\sigma_{\tilde{t}_1\tilde{t}_1}$ is the top squark pair production cross section for $\sqrt{s}$=1.96 TeV, ϵ_{ac} is the acceptance efficiency including tracking efficiency (0.78$\pm$.007) and jet reconstruction efficiency(0.96$\pm$0.03). In the data, tracking efficiency is obtained with a sample of triggered di-muon events from $Z \to \mu\mu$. It is found that there is a dependence of tracking effciency on muon directions. Because of this η dependence tracking effciciency needed to be parameterised[10]. In our analysis we have used the same parametrization for tracking efficiency, which is about $\sim 65\%$. The effective luminosity $\tilde{L} = L.c$, where c is the correction factor due to the trigger efficiency, muon identification and isolation efficiency [10]. With the correction factor, the effective luminosity turns out to be $\tilde{L}$ =81.8 $\pm$ 9.1 pb^{-1} where as the measured luminosity is 104pb^{-1}. In the calculation of cross section limits we have used this effective luminosity along with its error. In Table 1, we present, for various choices of $m_{\tilde{t}_1}$, accepted efficiencies (ϵ_{ac}) which is basically kinematic selection efficiencies computed by `PYTHIA` after applying the selection cuts as described above, folded with jet reconstruction and tracking efficiencies. It is expected that the efficiencies increase with $m_{\tilde{t}_1}$ as for higher values of $m_{\tilde{t}_1}$ muons and jets become more and more harder.

Clearly, from the knowledge of $\sigma_{\tilde{t}_1\tilde{t}_1}, \epsilon_{ac}$ (see Table. 1) and $\tilde{L}$, the number of $\mu\mu$+jj events can be predicted using Eq. 6. It is reported [10] that there is only one event in the data and the estimated number of background events are to be 1.59$\pm$0.47; the uncertainties in background estimation are purely due to the systematic and statistical errors. Armed

with this information we attempt to find the cross section limits using the Bayesian method assuming flat prior cross section distribution for different choices of $m_{\tilde{t}_1}$. In Fig.1, we display the limits of top squark pair production cross section by solid lines for various $m_{\tilde{t}_1}$ values and for two choices of ϵ^{μ}_{br} =0.5 and 1. The dashed line represents the predicted theoretical Born level cross section multiplied by K-factor(=1.3) [20] [3]. This figure clearly shows that the top squark mass upto $m_{\tilde{t}_1} \gtrsim$ 188(104) GeV is ruled out for ϵ^{μ}_{br}=1.0(0.5). We want to emphasize here that the limits of $m_{\tilde{t}_1}$ as shown in Fig.1 is completely model independent. The limiting values of top squark pair production cross sections as shown in Fig.1 and Eq. 6 enable us to predict upper limits of ϵ^{μ}_{br} for each value of $m_{\tilde{t}_1}$. In Fig.2, for various choices of $m_{\tilde{t}_1}$, we present the maximum values of ϵ^{μ}_{br} at 95% C.L, which are allowed by existing dimuon data. As for example, for $m_{\tilde{t}_1}$=100 GeV, the limiting value of top squark pair production cross section from data forbids ϵ^{μ}_{br} $\gtrsim$48%, otherwise top squark signal in this channel could be observed. The shaded region in Fig.2 is excluded at 95% C.L and certainly, it is a model independent prediction. Clearly, for $m_{\tilde{t}_1}$ $\gtrsim$180 GeV there is no limit on ϵ^{μ}_{br} since event rate is negligible for smaller values of cross sections in this mass range. It is already mentioned that in a given model the branching ratio ϵ^{μ}_{br} is controlled by the model parameters. Recall that the decay width of the channel, Eq. 4, is very sensitive to λ'_{23j} RPV coupling and mixing angle $\theta_{\tilde{t}}$. In addition to that the branching ratio,ϵ^{μ}_{br}, is also indirectly controlled by, mainly by M_2, μ and $\tan\beta$, which actually determine the total decay width of $\tilde{t}_1$ in all RPC decay channels. Hence, for a given SUSY parameter space the total decay width of $\tilde{t}_1$ in all RPC channels is fixed. Consulting eq.5 and for a fixed value of $\cos\theta_{\tilde{t}}$ one can obtain the limiting values of RPV coupling λ'_{23j} from the upper limits of ϵ^{μ}_{br}. Following this strategy, for the purpose of illustration, in Fig. 3, we display the excluded region in the $m_{\tilde{t}_1} - \lambda'_{23j}$ plane for two sets of values of $\tan\beta$=5(Fig.3a) and 30(Fig.3b) setting the SUSY parameters to M_2 = 130 GeV, μ = 500 GeV. The other SUSY parameters which are involved, but not very sensitive to our results are shown in the figure caption. This selected set of SUSY parameters determine the value of $m_{\tilde{\chi}^{\pm}_1}$ =122(125) GeV; $m_{\tilde{\chi}^0_1}$ =63(65) GeV. In each figure, we present excluded region for two nearly extreme values of $\cos\theta_{\tilde{t}}$=0.95 and 0.02. These figures indicate that the RPV coupling λ'_{23j} is bounded roughly by $\sim 10^{-3} - 10^{-4}$ for the region of parameter space where $m_{\tilde{t}_1} \lesssim m_{\tilde{\chi}^{\pm}_1}$ and $\tan\beta$=5(see Fig.3a). For higher $\tan\beta$ case(=30), this limit turns out to be smaller approximately by one order of magnitude (see Fig.3b). However, the limit becomes weaker for the scenario where $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}^{\pm}_1}$, because of the fact that in this region, the decay mode, $\tilde{t}_1 \to b + \tilde{\chi}^{\pm}_1$ opens up and dilutes the dimuon plus dijet event rate. The enhancement of RPV decay width with the increase of $\cos\theta_{\tilde{t}}$ value results more excluded region than the region for low value of $\cos\theta_{\tilde{t}}$. On the other hand higher value of $\tan\beta$(=30) results enhanced loop decay width, Eq. 2, costing branching ratio in the RPV decay channel, which eventually exclude comparatively narrow region, as shown in Fig.3b. It is interesting to note that limits obtained from the present analysis in the $\tilde{t}_1$ NLSP scenario for $m_{\tilde{t}_1}$ $\lesssim$180 GeV are comparable to the limits obtained from the neutrino data. Needless to say that this conclusion is very

[3] Although the value of K-factor depends on the choice of QCD scales, but for the sake of simplicity we assumed it to be fixed.

much SUSY parameter space dependent and holds for that region of parameter space where top squark is light($\lesssim$ 180 GeV) and appear to be the NLSP.

In summary, we have computed the top squark pair production signal cross section in the di-muon plus dijet channel and compared the event rates with the existing data in D0 detector at the Tevatron Run-II experiment. This type of signal occurs in the context of RPV SUSY model in the presence of lepton number violating coupling λ'_{23j} which is assumed to be the dominant one. Our analysis rules out the top squark mass, $m_{\tilde{t}_1} \gtrsim 188(104)$ GeV in a model independent way for the branching fraction of top squark in the muon plus jet channel, ϵ^{μ}_{br}=1(0.5)(see Fig.1). The top squark pair production cross section limits obtained from data for each $m_{\tilde{t}_1}$ restrict the value of ϵ^{μ}_{br}(see Fig.2). In the framework of RPV SUSY model, the upper limits of ϵ^{μ}_{br} can be translated to the upper limits of λ'_{23j} coupling for a given set of SUSY parameters. We found that our predicted limits on λ'_{23j} are very close to the limits obtained from neutrino data for a certain region of SUSY parameter space where $m_{\tilde{t}_1}$ behaves like NLSP and $m_{\tilde{t}_1} \lesssim 180$ GeV.

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$m_{\tilde{t}_1}$(GeV)	Detection efficiency(%) $\mu^+\mu^-$
100	1.52
120	3.4
140	6.67
160	10.4
180	13.8
200	15.7
220	17.2

Table 1: Di-muon plus di-jet detection efficiencies for various $m_{\tilde{t}_1}$.

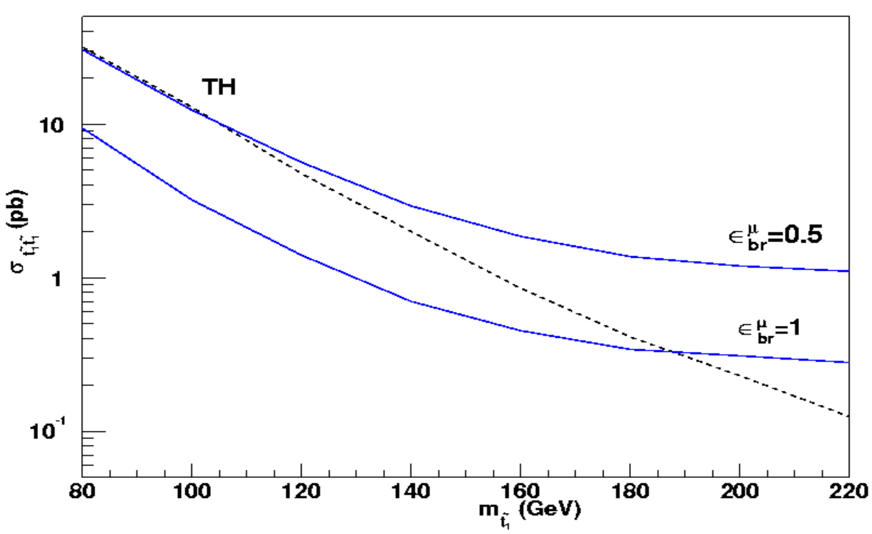

Figure 1: The top squark pair production cross section limits using data at 95% C.L. for ϵ^{μ}_{br} =1 and 0.5(solid lines). The dashed line represents the theoretical prediction.

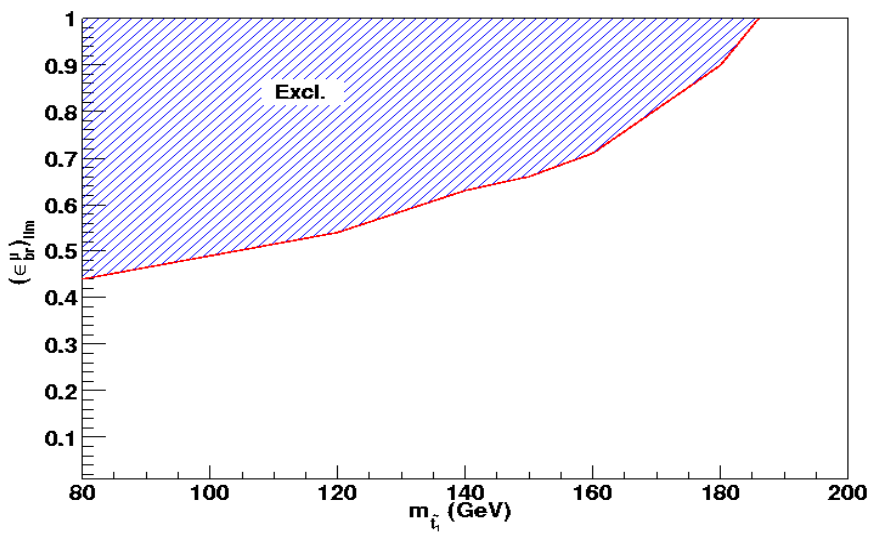

Figure 2: The excluded region(shaded area) by dimuon data at 95% C.L.

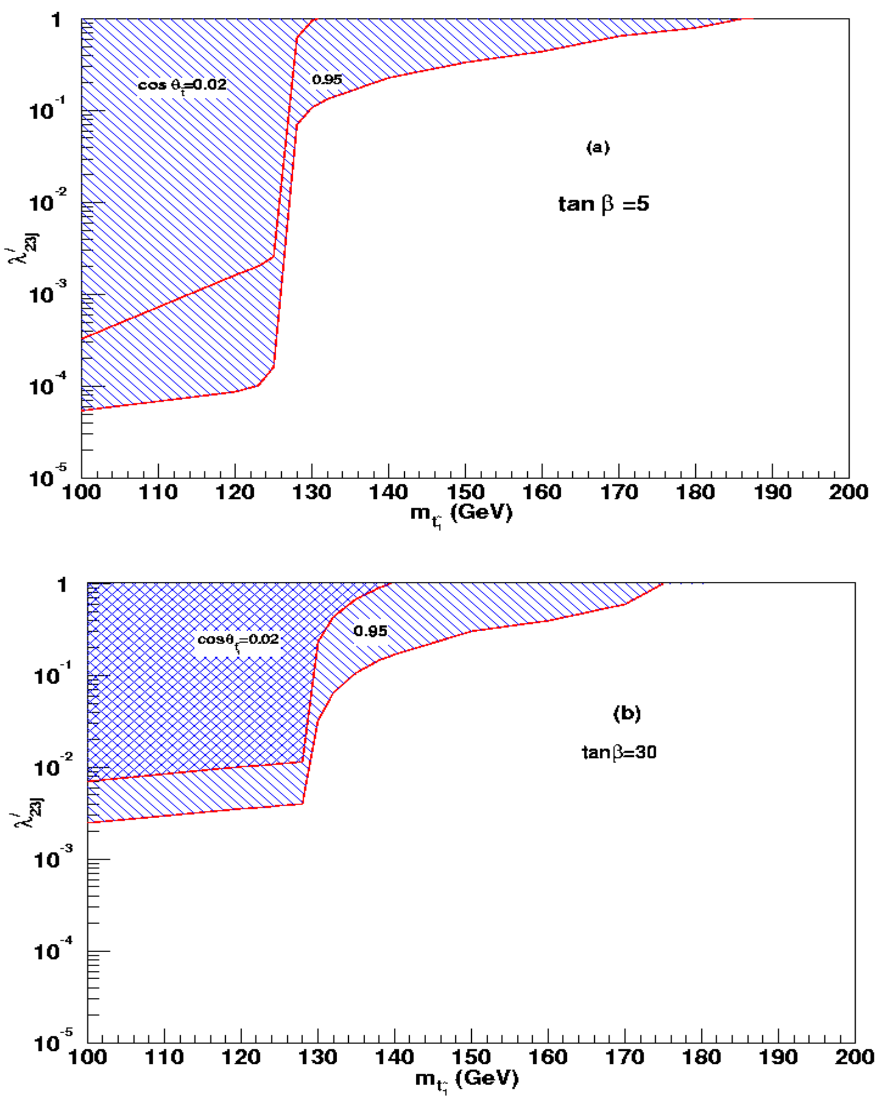

Figure 3: The excluded region(hatched) by di-muon data at 95% C.L. The SUSY parameters are: M_2 =130 GeV, μ=500 GeV, $m_{\tilde q}$ =300 GeV, $m_{\tilde \ell}$ =200 and A-terms=200 GeV.